

EVA Development and Verification Testing at NASA's Neutral Buoyancy Laboratory

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As an early step in the preparation for future Extravehicular Activities (EVAs), astronauts perform neutral buoyancy testing to develop and verify EVA hardware and operations. Neutral buoyancy demonstrations at NASA Johnson Space Center's Sonny Carter Training Facility to date have primarily evaluated assembly and maintenance tasks associated with several elements of the International Space Station (ISS). With the retirement of the Shuttle, completion of ISS assembly, and introduction of commercial players for human transportation to space, evaluations at the Neutral Buoyancy Laboratory (NBL) will take on a new focus. Test objectives are selected for their criticality, lack of previous testing, or design changes that justify retesting. Assembly tasks investigated are performed using procedures developed by the flight hardware providers and the Mission Operations Directorate (MOD). Orbital Replacement Unit (ORU) maintenance tasks are performed using a more systematic set of procedures, EVA Concept of Operations for the International Space Station (JSC-33408), also developed by the MOD.

This paper describes the requirements and process for performing a neutral buoyancy test, including typical hardware and support equipment requirements, personnel and administrative resource requirements, examples of ISS systems and operations that are evaluated, and typical operational objectives that are evaluated.

Nomenclature

EVA = Extra-vehicular Activity
ISS = International Space Station
MOD = Mission Operations Directorate
NBL = Neutral Buoyancy Laboratory

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ORU = Orbital Replacement Unit

I. Introduction

The first goal in the 2011 NASA Strategic Plan states: “Sustain the operation and full use of the International Space Station (ISS) ... to 2020 or beyond.” The second goal states “Develop competitive opportunities for the commercial community... by providing expert advice, access to NASA facilities, and development funding.” Human spaceflight is at a crossroads between government leadership and commercialization/privatization. Whatever direction is ultimately taken, major NASA facilities and their capabilities as national assets must be preserved.

The Neutral Buoyancy Laboratory (NBL), a facility at NASA Johnson Space Center (JSC) is an essential tool for design, testing and development of the International Space Station and future NASA programs. For the astronaut, the facility provides important pre-flight training for extravehicular activities (EVA) and with the dynamics of body motion under weightless conditions. Neutral buoyancy demonstrations are performed to evaluate several assembly and maintenance tasks associated with elements of the International Space Station (ISS). The NBL has also been used for evaluations related to surface exploration and ISS commercial visiting vehicles. This trend will increase with the retirement of the Space Shuttle and the current space policy intent to transition ISS transportation services to commercial providers while focusing NASA’s efforts on exploration beyond low earth orbit. Extension of ISS operations to 2020 and beyond puts increasing pressure on return on investment in utilization and science yield. Criticality of every EVA is increased by reliance on partner nation vehicles and possibly a reduced scope Orion and/or commercial vehicles for continued ISS operation. ORUs originally intended for replacement may see repair or in-place refurbishment instead. The NBL will assume increasing importance for test and training. New fidelity and flexibility requirements may be imposed on mockups may due to the development of new EVA and IVA tasks. EVAs will be conducted in the current NASA EMU as well as the Russian Orlan. The NBL may also be involved in assessment and training of a next generation NASA and/or commercial EVA suit system..

As an early step in the preparations for future Extravehicular Activities (EVAs), astronauts perform NBL testing to develop and verify EVA hardware and operations. These tests are coordinated and conducted by the EVA Development and Verification Test (EDVT) Team. The EDVT Team has supported the development and verification testing of International Space Station (ISS) modules and truss structures, assembly tasks, maintenance tasks, and ISS, Shuttle, visiting vehicle, and National Space Transportation (NSTS) tools and hardware for more than 15 years. The majority of the tools and hardware analyzed and tested were EVA-related and Class III hardware. This team has worked under the direction of the Tools and Equipment Branch (EC7) of the Crew and Thermal Systems Division (CTSD) at the National Aeronautics and Space Administration (NASA) and has supported the EVA Projects Office (XA) and the Space Suit and Crew Survival Systems Branch EC5 of the CTSD. The EDVT team is responsible for the coordination and implementation of development and verification testing at the NBL with test conductors and aerospace human factors engineers that perform worksite analysis. The team is also staffed with divers certified to support NBL tests both on SCUBA and on Surface-Supplied Diving System (SSDS) with voice communication.

Other NASA organizations participating in NBL development and verification tests include the EVA Project Office (XA), the EVA, Robotics, and Crew Systems Operations Division (DX), and the Astronaut Office (CB). Evaluations are also supported by personnel from several contractor organizations such as the Engineering and Science Contract Group (ESCG), Raytheon (RAY), United Space Alliance (USA), EVA/Extravehicular Robotics (EVR), Goddard Space Flight Center (GSFC), The Boeing Company or Lockheed Martin. Other space agencies and their respective contractor organizations such as the Japan Aerospace Exploration Agency (JAXA), the Canadian Space Agency (CSA), MacDonald Dettwiler and Associates (MDA) may also support tests.

This paper discusses the requirements, approaches, and process undertaken for performing a neutral buoyancy test and describes the types of systems and operations that are evaluated in neutral buoyancy tests. It establishes the relevant hardware and support equipment requirements and identifies the specific hardware and operational objectives evaluated. This paper also addresses ways in which NBL development and verification testing can be applicable to the future trends of NASA and growth of the commercial space transportation industry.

II. Test Philosophy – Why Do NBL Testing?

A. Test Rationales and Approaches

Neutrally buoyant testing has been used since the beginning of manned spaceflight to prepare for missions to low earth orbit to develop hardware and verify requirements. By providing a simulated gravity, a test subject is able to

position in ways that can not be done in any other testing facility. Hardware designers benefit from this test methodology by gaining valuable operability insight from the Extravehicular Activity (EVA) crewmembers during the earliest phases of design. Likewise, the operations community benefits from neutrally buoyant testing by gaining early access to hardware designs and by being able to make inputs to the developers that will improve the ease of operability, safety, and increase mission success for a given piece of hardware. Positioning, torquing, and reach evaluations are specific examples that allow test subjects the ability to feed direct comments back to design teams on minor tweaks and major redesigns of hardware.

Until recently, software modeling capabilities were insufficient to analyze a large piece of integrated hardware and verify requirements. Hardware developers relied on neutrally buoyant testing to verify EVA requirements leading to certification for flight, including the International Space Station (ISS) hardware developers. Today, even with the benefit of easily manipulatable ISS models to build and verify new hardware, some scenarios still require testing for requirement verification closure. Most often these cases represent a requirement non-compliance identified via analysis; the testing provides the rationale to accept the hardware that is in violation of EVA requirements. Other verification test cases arise for hardware providers that do not have in-house EVA expertise or models and choose not to hire NASA for this requirement verification service.

Highly choreographed tasks benefit greatly from being tested and practiced in a neutrally buoyant facility. The 126 EVA sorties necessary to assemble the International Space Station (ISS) are the most complex timelines performed in the history of human spaceflight. The EVA crewmembers efforts varied from individual tasks to partner tasks to robotically assisted tasks. The orchestration of an EVA timeline to complete all mission objectives within the allocated EVA time requires a skillful composer. The success of these EVAs can be credited to the benefits gained from the use of the NBL, in addition to the hardware work of a dedicated team of engineers, scientists and operators.

B. Applicable Phases

The traditional hardware design life cycle employed at NASA is a formal structure of Requirements and Design Reviews that ensure the hardware is meeting its design goals. The NBL provides a hands on input into these design milestones by providing a full three dimensional evaluation. These evaluations can be used at varying levels of design fidelity to assist engineers with both design and requirements decisions.

Neutrally buoyant testing occurs at three distinct phases of a development cycle: pre-Preliminary Design Review (PDR), between PDR and Critical Design Review (CDR), and after CDR prior to flight. In the pre-PDR phase, the broad hardware concepts are tested, sometimes multiple times. Between PDR and CDR, the hardware design is tested for operability. Following CDR and prior to flight, the final hardware design is again tested by the operators. Minor hardware modifications can be accommodated in this phase before delivery to be processed for launch.

Pre-Preliminary Design Review (PDR) Phase

Pre-PDR includes the development of requirements. During the requirements phase of any project questions arise as to how the hardware will interface with humans. When considering micro gravity tasks, the NBL has been utilized by building low fidelity hardware and evaluating requirement concepts to determine acceptability prior to spending large budgets to find out the requirement wasn't adequate.

During the Preliminary Design Phase, the NBL has been used for full scale mid fidelity mockups of space vehicles and International Space Station modules. EVA tasks for assembly, repair, and maintenance tasks have been performed. These evaluations generated very specific hardware design feedback to designers to assist them with areas of compliance and areas where questions to the compliance were in question. These evaluations have been instrumental in the assembly of the International Space Station, Hubble Space Telescope, and other EVA's that have been performed since the NBL was built.

Between PDR and CDR (Critical Design Review) Phase

Between PDR and CDR, the hardware developer presents a design with a shape, a size and functional needs that are likely to reflect the final hardware configuration. Testing occurs to determine if the design operational expectations can be performed by the EVA crewmembers. Are the handling aids located in a position to best allow the crewmember to manage the hardware while performing the task? Does the new hardware fit in the airlock and through the hatch with two suited crewmembers and their tools? Can the crewmember reach the contingency release mechanism if a failure occurs? Can the tools be manipulated to perform the desired task? Examples of this include installation and activation steps of a new element, layouts of external stowage pallets, disassembly of ISS to integrate new maintenance capabilities, and development of new EVA tools. A new element that requires EVA assistance for installation might test access of the EVA crewmember to the attachment mechanisms, acceptability of

the EVA worksite to attach connectors and deploy components, and ability of the astronaut to route cables from the new hardware to the connection point on ISS. An external stowage pallet layout must balance EVA and robotic requirements such that compliance of EVA requirements does not preclude compliance with robotic requirements, and vice versa. On orbit anomalies of the ISS have prompted the Program to request new maintenance and repair capabilities beyond the original design intent of the hardware. In these cases, testing has occurred to determine if EVA crewmembers can remove panels to access components not designed to be EVA maintained, lubricate mechanical joints, replace components, and install new components. The developers of a new EVA tool design would test if the tool can be used at the intended worksite and if the tool can be handled safely by the suited crewmember.

These evaluations fill the gap where a software model can't answer the questions. For example there were many cases where the keep out zone around electrical connectors on the ISS had to be violated. The software models assisted on many but due to the positioning of the crew during the operation, they were limited on many. The NBL provided the necessary hardware to flight specifications to ensure that the tasks could be completed successfully on orbit in a timely manner.

Between CDR and Flight Phase

After the hardware design is locked down and on its way to being accepted by the government or customer, the NBL continues to assist the designs by answering questions that come up during normal integration activities. As hardware changes due to changes in materials, structural load concerns, or other integrated issues, the NBL provides the ability to re-assess whether these changes are acceptable. For spaceflight hardware this is a tremendous budget savings and in many cases the difference between success and failure.

Up to this point in the process, all NBL evaluations of the hardware have been focused primarily on the feasibility of the task. Once the NASA program office determines a task will be performed on a specific EVA and the EVA team is assigned, efficiency and integration with other tasks in the EVA becomes the primary concern. The basic steps for integrating a task into an EVA are given below.

1. Program determines a need to perform the task or group of tasks on a specific EVA
2. EVA team provides an estimate as to what tasks will fit into a 6:30 EVA; if there appears to be extra time, the team will attempt to incorporate tasks from the "homeless list" (lower priority tasks that wouldn't drive an EVA, but will put us in a better posture for future operations) that work well with the high priority tasks on the EVA.
3. Program prioritizes all tasks for EVA/mission
4. EVA team integrates data and skeleton procedures from hardware providers and development runs into a detailed EVA procedure. A cribsheet is also produced to guide the crew through contingencies associated with hardware.
5. Crew performs end-to-end NBL run; Crew and EVA team debrief after each run
6. Procedures, tasks, and/or hardware are modified to increase efficiency and allow all tasks to fit into a single EVA
7. Crew performs 2 – 6 additional NBL runs (number depends on task complexity and amount of time before EVA is to be performed); additional tweaks to procedures and hardware may be made after each run.
8. Final procedures and cribsheet are written
9. Crew performs EVA on orbit

To integrate a task into an EVA, the EVA team will often have to reconsider the order of steps in procedure, required number of crew to perform the task, worksite restraint method, tools use, and hardware design. The order of the steps in a procedure may seem perfectly logical when evaluating a task on its own. However, when considering the EVA as a whole, it may make sense to change the order of the steps in the task to minimize crew translation or minimize impact to a higher priority task. The number of crew performing the task may also play a role in the step order. In some cases what was determined to be a 2 person task in a development run must be converted to a 1 person task to allow all objectives to be completed in an EVA. To convert a 2 person task to a 1 person task, additional time, tools, and changes to the hardware may be required. Worksite restraint methods may be modified based on the number of crew performing a task as well as the availability of items like APFRs and the SSRMS. For example, if the Space Station Remote Manipulator System (SSRMS) is required to be used at a nearby worksite during the EVA, the team may consider using it for the task in question because of the additional stability it

provides. The inverse is also true due to the overhead associated with the SSRMS; the team would try to find a way to perform a task without the SSRMS if this was the only task requiring SSRMS operations on the EVA.

In many cases the crew carries tools and hardware for multiple tasks in a single EVA bag to reduce the number of trips back and forth to the airlock. Therefore, it is desirable to use the same tools for multiple tasks to keep the bag size at a minimum and reduce the number of tools the crew has to look through to find the one they need. In some cases this may drive the crew to use a tool or bag that may not be optimal for one task, but is required for another task. Additionally, the team may need to use an EVA tool in a way that it was not certified for; this request will be evaluated by the tools team.

Even though development testing may have determined that the hardware design was adequate to perform a task, once the task is integrated into a time constrained EVA and factors such as worksite restraint method or number of crew performing the task is changed, the hardware design may no longer be adequate. Once the EVA team realizes that their plan may drive a hardware change, they start communicating with the hardware provider to determine the feasibility of making the change. Examples of changes that have been made are: build custom bag to carry hardware, remove thermal blanket before flight rather than having the crew do it during an EVA (requires additional thermal analysis), add Sharpie marks/labels to assist with alignment or identify key interfaces, and cut lanyards that tethered multiple pieces of hardware together.

In addition to the hardware design inputs, these evaluations in conjunction with operations provide the ability to be better prepared for operational tasks. Training is conducted on the same or similar hardware of varying levels of fidelity to focus the operators on the proper tasks needed of the hardware.

C. Verification Methodology Options

Requirements are verified for compliance via test, analysis, inspection, or a combination of methods. The verification method is determined at the time the requirement is written and approved for a project. As discussed above, the verification method of EVA requirements has evolved over time as the analysis tools have grown in robustness. It is a common opinion in the Systems Engineering community that a well designed test is the preferred method of verification of requirements, especially for components within highly integrated systems. Analysis is an excellent methodology when there are few, if any, assumptions to be made while writing the analysis equations. That is, analysis works well in an equation that is well defined, such as the thermal performance of a given metallic. Analysis of a complex system becomes a simulation; and all simulations are based on assumptions. The more assumptions required, the less accurate the results of the analysis. The third methodology is verification by inspection. For example, the requirement that a piece of hardware handled by an EVA crewmember must include a tether point can be verified by inspection of the drawing to verify that said tether point exists. Similar to analysis, the more complex the requirement, the more difficult it is to verify by inspection, and therefore inspection becomes a less desirable method for complex requirements.

D. Crew Selection

Choosing the right crew to support an NBL operation is the key to a successful test. All crewmembers are qualified and can lend helpful suggestions but given the cost of the operation, the impact to expensive spaceflight hardware, and the budget and schedule constraints always seen at NASA, the right crewmember is the one that has a specific understanding of the hardware being evaluated. This does not always mean EVA experience, however usually it is required.

Other considerations are anthropometric ranges and skill level. The anthropometric data is kept on all crews and is a tool that is helpful in ensuring that a range of sizes are evaluated on any given test. Since all things EVA come down to the ability to put the worksite in one's personal work envelope, it is imperative when building hardware and testing it in the NBL that it work with from small crewmembers to tall ones. Usually there are multiple ways to do any given tasks and the NBL assists with finding those ways. However there are times where it requires longer arms or shorter reach from a specific worksite. For these operations a size selection is required prior to assigning crewmembers to perform testing at the NBL.

Performing EVA is a difficult task and while all crewmembers are trained to do it, not all do it as well as others. Therefore the skill level must be considered when selecting a crewmember for a test. It is always beneficial to have someone who has the highest level of skills demonstrate that they can perform tasks in the NBL. It is sometimes more important to verify that a moderately EVA-skilled crewmember can perform the task and protect that when required to be performed on orbit, most crewmembers will have a good chance of being successful.

III. Development vs Verification

Development and Verification tests are performed differently from each other in a few important manners. The determination is made jointly by the hardware provider and the EVA Office representative. Though the test subject sees very few of the differences, the hardware providers and test team members are acutely aware of the differences. A verification test requires a more rigid set of standards as the results of the test will be used to directly close requirements necessary to certify the hardware and deliver it for flight.

A. Methods of Verification

A verification test is executed differently from a development test. In a verification test, the accuracy of the test equipment as compared to the flight hardware must be quantified and assessed for acceptability. In a neutrally buoyant test for verification of EVA requirements, this boils down to a dimensional assessment of the mockup. For example, to verify that a worksite meets the EVA worksite outfitting requirements with handling aids placed appropriately, it is critical that the test mockup dimensionally represents the flight hardware. The standard that is practiced is dimension accuracy to ± 1 inch. This dimension must be measured in the test configuration. Large NBL mockups are disassembled to be moved in and out of the water. The results of a dimensional assessment of the mockup while sitting dry on the deck will not match the result of a dimensional assessment performed after the mockup has been disassembled, moved into the NBL, and reassembled underwater.

A. Test Description

Each crewmember evaluates all operations under investigation. Minor hardware and procedural modifications are incorporated during the test series as the test team deems appropriate. All modifications are documented in the test report.

JSC's NBL consists of a pool that is 202 ft long, 102 ft wide, and 40 ft deep Figure 1 and has standard filtering and chlorinating equipment. Two Extravehicular Mobility Units (EMUs) with planar Hard Upper Torsos (HUTs) are provided for each test run. An environmental control system provides nitrox breathing air and water cooling through life-support umbilicals attached to the EMU.



Figure 1. NBL

To ensure the accuracy of each simulation's findings, the following guidelines for test mockups and proper test performance are consistent for all simulations:

- a. All procedures and hardware reflect the on-orbit configurations and operations within the scope of the simulation objectives.
- b. Test requirements include the accurate collection of timed audio/video coverage of test activities, as well as all comments made by the test subjects about the techniques and equipment.
- c. The test is developed with the participation of the test team and principal investigators.
- d. All test requirements, operations, data, and results are documented in a written report and maintained for historical record purposes.

B. Test Article Configuration

NBL development tests typically use various worksites in the standard NBL pool configuration for evaluation of objectives. A typical NBL pool configuration post-Shuttle includes the full ISS truss complement, all ISS elements including Nodes, Russian segments, airlock, and pallets, the Space Station Remote Manipulator System (SSRMS) simulator, and the H-II Transfer Vehicle (HTV). Elements are configured or re-positioned according to the specific needs dictated by the objectives of a particular test series.

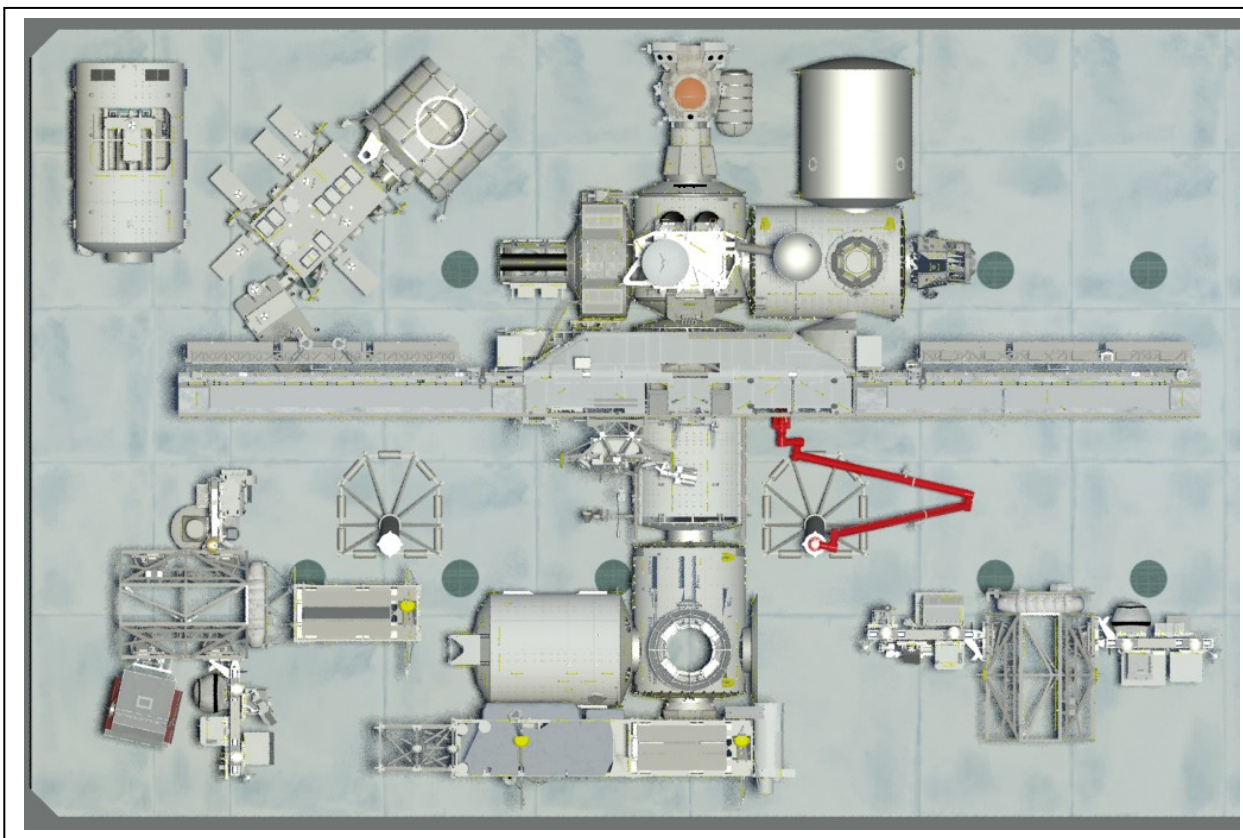


Figure 2. Typical NBL Pool Configuration

B. Test Operation

Neutral buoyancy evaluations consist of the following events:

- a. A 4-hour scuba run.
- b. A 6-hour engineering run.
- c. Three 6-hour suited crew runs, with two astronauts each day.

During each suited crew run, two crewmembers perform all test operations outlined in the Detailed Test Procedures (DTPs) developed for that particular evaluation.

C. Operational Assumptions

The DTPs to simulate on-orbit operations are based on flight procedures developed by the MOD and/or EVA Analysis Reports (EARs) generated by the hardware providers. The DTPs to simulate ORU maintenance operations are based upon the Concept of Operation (COO) document developed by MOD and the EARs generated by the hardware providers. Certain assumptions are made to generate the procedures. The following assumptions can affect the configuration of the test articles, stowage of EVA tools, and performance of test operations:

- a. All equipment and safety tethering protocols are followed as allowed by limitations in the test article configuration and time allotted in the pool.
- b. Once at a worksite, all EVA tools used to support “end-to-end” testing operations are managed by the test subjects without utility diver intervention. If a test operation is not being performed as an “end-to-end” evaluation, necessary tool assistance is provided by the utility divers. It is beyond the scope of the test objectives to retrieve tools from their assigned stowage locations (e.g., Crew and Equipment Translation Assembly (CETA) tool box, airlock tool box) for any of the test objectives.

IV. Hardware (Mockups)

Test hardware and mockup development starts with the identification of the test objectives and the particular EVA tasks that are involved.² The TC determines the preliminary translation paths, necessary tools, equipment to be interfaced with and develops a preliminary hardware requirements list. The TC contacts the NBL Flight Lead (FL) and provides the FL with these initial requirements and works with the FL to determine if any new mockup hardware is required. The FL determines the availability of mockups in the NBL inventory that meet the test requirements. The FL notifies the TC of any mockups required to support the training that are not in the NBL inventory. For hardware that is not available at the NBL, the TC determines if the training hardware is available from an external (to NBL) source or if a new mockup is required to be fabricated. If a new mockup must be fabricated, CB or DX submits a Change Request (CR) to the NBL for the development of training hardware if new hardware is required. The NBL develops the hardware per the requirements specified in the CR and per “NBL Mockup and Training Hardware Requirements,” DX12-SLP-014, which describes how hardware must be built to function and survive in the unique working environment of the NBL.

If the TC determines that training hardware is available from an external source and that the hardware meets the requirements of DX12-SLP-014, the TC interfaces between the external source and the NBL FL to make arrangements for transfer of the hardware and supporting documentation to the NBL. The EDVT team may also create hardware for tests, and has provided several mockup Station modules. Small scale hardware and mockups are manufactured at the Engineering Development Facility (EDF). In some cases, the development of hardware or mockups requires support of other ESCG groups and organizations. This support varies in scope from minor non-structural volumetric mockups, to fully integrated and verified structural elements.

Dimensionally accurate mockups usually involve design, drafting, and manufacturing support. Structural mockups always involve full support from design, drafting, quality, and manufacturing. Quality controls are employed for manufacturing processes (welding, fasteners, etc.). See Figure 3, Figure 4, Figure 5, and Figure 6. Support structures usually involve manufacturing support, and may involve structural analysis and released drawings.



Figure 3: NBL Small Hardware Example - Neutrally Buoyant Round Scoop

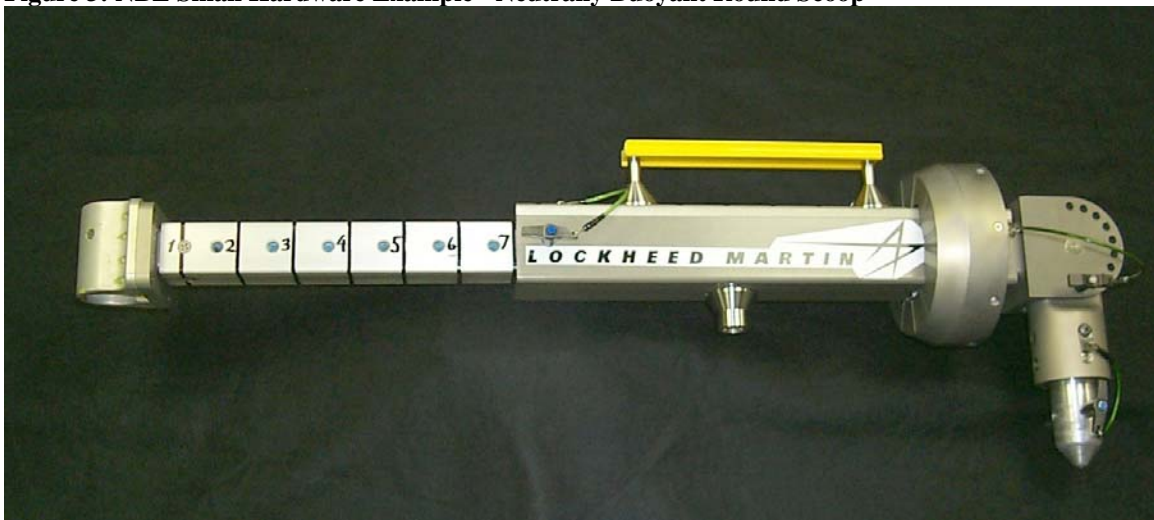


Figure 4: NBL Small Hardware Example - Worksite Interface Extender



Figure 5: NBL Large Mockup Example - Node 2

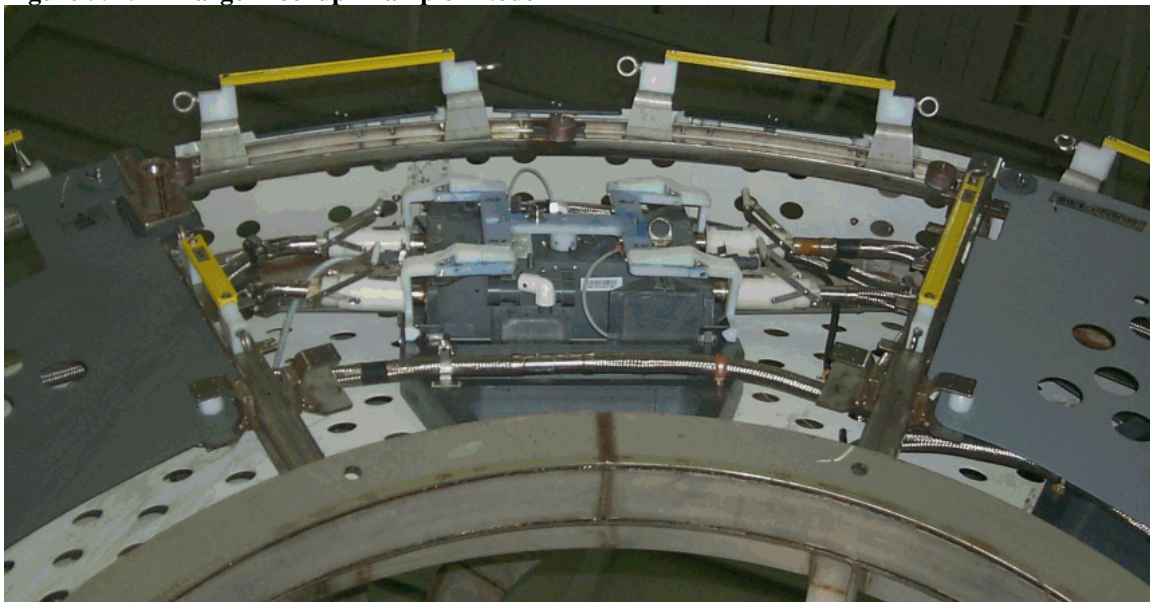


Figure 6: NBL Large Mockup Example - Node 2 Heat Exchanger Worksite

Mockup Fidelity

Fidelity of mockups and hardware is based on training and testing requirements and is specified in the CR. Since development testing involves shorter timelines and unique requirements, mockup fidelity is often a trade-off between cost, fidelity, and schedule. The TC, Flight Lead, Crew Office representative and overall test team collaborate to determine the best course of action at minimal cost and schedule impact that will facilitate subjects

evaluation of the hardware and objectives. **Error! Reference source not found.** Defines the various fidelity requirements of class and functionality to which mockups are designed.

Table 1. Mockup Fidelity Classification⁴

PHYSICAL		FUNCTIONAL CLASS			
		A	B	C	D
		FLIGHT LIKE	FUNCTIONALLY ACTIVE	OPERABLE	STATIC
I	FLIGHT ASSEMBLY TOLERANCE SIMILAR MATERIAL EXACT CONFIGURATION	I.A.	I.B.	I.C.	I.D.
II	RELAXED ASSEMBLY TOLERANCE MIXED MATERIAL APPROXIMATE CONFIGURATION	II.A.	II.B.	II.C.	II.D.
III	APPROXIMATE DIMENSIONS OPTIONAL MATERIAL CANDIDATE CONFIGURATION	III.A.	III.B.	III.C	III.D.

Class I:

Class I mockups are typically used to support crew training and engineering verification.

1. Flight Assembly Tolerance: Built to flight dimensional specifications.
2. Similar Material: Materials used are of the same family and are characteristic of the flight material, but not necessarily of the same grade or specification (e.g., metals-metal, plastics-plastic, fabrics-fabric).
3. Exact Configuration: Appearance is like flight in all aspects (e.g. size, shape, color, orientation, location, etc.).

Class II:

Class II mockups are typically used for crew familiarization and design development.

1. Relaxed Assembly Tolerance: Not held to flight dimensional specifications. Margins to be specified by program.
2. Mixed Materials: Materials will be generally characteristic of flight, but not necessarily of the same family, grade or specification. Material shall be selected to optimally support the intended function.
3. Approximate Configuration: Appearance is similar to flight in most aspects (e.g. size, shape, color, orientation, location, etc.).

Class III:

Class III trainers are typically used for crew interface.

1. Approximate Tolerance: Held to volumetric approximations.
2. Mixed Materials: Materials support facility objectives.

V. Roles & Responsibilities - What Does it Take to Pull Together an NBL Test?

A. Test Team Personnel

The following test team members are responsible for test development and planning, coordinating facility integration, conducting the real-time test, and test resolution:

Test Engineer (Lead Test Conductor) Jacobs.....	EDVT/EC7
EVA Office Representatives/Test Requestors	NASA/XA
Principal Investigators/Test Requestors	Various
Mission Operations Representatives.....	USA/DX32
Crew Office Representatives.....	USA/CB
NBL Flight Lead.....	Raytheon/DX12
NBL Project Lead.....	Raytheon/DX12

B. EVA Development and Verification Test Team (Jacobs/EC7)

The EDVT team is responsible for the coordination and implementation of development and verification testing at the NBL. This process begins with a test request identified by the customer, that usually results in the assignment of a Principal Investigator who is responsible for the specific hardware/procedural evaluation. The EDVT team assigns a Test Engineer/Lead Test Conductor (TC) to the test who then initiates a kickoff meeting to establish the background, objectives, hardware, and pool configuration required to support the specific NBL test. This meeting usually involves representatives from each supporting organization (i.e. EC, MOD, XA, CB, and NBL Flight Lead). The TC then conducts weekly tagups/meetings with this group to outline the documentation and hardware requirements to support the NBL evaluation. The TC keeps weekly documentation on evolving test objectives, the hardware list, the test schedule, and the action item log. Once a time period has been established to conduct the test, this information is taken to the Long Range Planning scheduler to be added into the schedule.

During the test planning process the TC develops a Test Plan based on agreed objectives, hardware definition requirements, pool configuration, and preliminary procedures and prepares for the Preliminary Configuration Meeting (PCM), which is held one month prior to testing. The PCM covers objectives, pool configuration requirements (including whether the Station arm is required along with a list of mockups required), camera requirements, and mockups required with photos. The TC also provides an operational Hazard Analysis (HA) and if hardware is provided by the EDVT team, a hardware HA. If another organization provides the hardware, the TC ensures that this organization provides an HA for the hardware prior to the Test Readiness Review (TRR). Crew/Subject support for the test is arranged through CB and suit support is arranged through USA.

Two weeks prior to test activities, the TC submits pre-dive forms through the NBL pre-dive calendar which outline the overall test objectives, hardware, pool configuration, suit configuration, still photo and video documentation requirements. A pre-dive form is required for each run. Any guest divers for a run submit a guest dive request through the pre-dive calendar as well. TCs also submit tool matrix requests through the MOD which includes any EVA support tools that are required. The tool matrix form is used to check off which tools by their individual part and serial numbers. Based upon the submitted pre-dive forms the NBL Flight Lead generates

configuration checklists for each test run which are used to direct the NBL dive team to set up the pool configuration for the test. The TC provides feedback to the NBL Flight Lead for the configuration checklists.

With the support of the required organizations and Principal Investigator the TC generates Detailed Test Procedures for each of the test objectives. The TC also prepares and participates in the NBL Test Readiness Review Board (TRRB), which is held 1-2 weeks prior to the test, depending on discretion of the NBL flight lead and whether the hardware has previously been in the NBL. The TC prepares and conducts a crew/subject briefing just prior to all hardware/mockups being placed in the water. Thus the briefing is usually held in conjunction with the NBL TRRB. This briefing provides subjects with details on the test objectives, pool configuration, and hardware as well as a hands-on familiarization with the mockups and any specialty tools that are to be used. To verify test configuration and further familiarize crews/subjects with the hardware/mockups and test setup, TC's conduct a SCUBA run prior to any suited runs. This can be conducted from console with in-water support or solely in-water.

On each day of the NBL test series the TC submits a signed Test Conductor Checklist to the Test Director and completes the NBL Anomaly Log if any anomalies are found during the evaluation (mockup configuration, tool breaks, etc). At the conclusion of the test series the TC generates a Quick Look Report, usually within three days of the last NBL evaluation. Within 8 weeks after the last NBL run, depending on receipt of CCR, any additional loads data or data that may require longer time to compile, the TC generates a Test Report. This report encompasses any delta objectives, hardware changes, final test configuration, observations and results, Detailed Test Procedures, along with the entire CCR as part of the Appendix.

C. EVA Office (XA)

The EVA Office representative is the liaison between the hardware provider and the NASA ISS EVA team. The EVA Office imposes EVA requirements on the hardware as appropriate to meet the planned and contingency mission objectives set forth by the ISS Program. Based on the hardware design and operations, the EVA Office representative, along with the full NASA EVA team, determine which aspects of the design require development and/or verification testing. The EVA Office representative role varies based on the spaceflight experience of the hardware provider. If a new hardware provider is developing their first piece of hardware to be handled via EVA, there are many iterations of expectation discussions between the hardware provider and the EVA team. If the hardware provider has significant experience developing hardware for ISS, the EVA Office rep is oft able to concur with the plans proposed by the hardware provider. The goal is to develop a piece of hardware that can be safely and successfully installed and maintained by the EVA crewmember. Discovering an incompatibility once the hardware has arrived at the International Space Station is a costly problem this team works to avoid.

D. Mission Operations Directorate (MOD), EVA Operations (DX3)

The primary role of the MOD representative (i.e., EVA Operations) is to provide expertise as to how this type of operation would be performed in space and to help identify the key areas to focus on in the test. MOD trains crew for EVAs and supports the EVAs from mission control. These experiences give the MOD representative unique insight into the best tools, body restraint method, and operational order to use for a given task. The products that MOD would typically provide are: EVA procedures, foot restraint settings, and a list of tools to use for the evaluation. The MOD representative will also write Change Requests (CRs) to have mockups built and assist with coordination with the NBL flight leads. During the test, the MOD representative is available for technical questions and real time problem resolution if the initial approach is unsuccessful.

D. NBL Flight Lead (DX12)

A Flight Lead is assigned to each NBL development test series. The Flight Lead is the primary NBL point of contact for the Test Requestor and/or TC. Flight Leads are assigned by the NBL Chief and can consist of a NASA or contractor employee. The Flight Lead assists the Test Requestor and/or TC through all stages of scheduling, planning, approval, preparation and performing an NBL Event. In preparation for the test the Flight Lead provides oversight for mockup development to ensure mockup designs meet requirements specified by the TC and NBL mockup and trainer requirements. The Flight Lead may also have to work with other Flight Leads and respective TC's to resolve conflicts between 1G training sessions, in water training sessions and real time flight support.

For each event the Flight Lead develops the configuration set-up checklist to support the Pre-dive requirements submitted by the TC. During the event itself the Flight Lead monitors progress and is on-call to assist in resolving any issues or coordinate any TC requested changes.⁵

E. NBL Project Lead (DX12)

The Project Lead (PL) assists the Flight Lead with hardware and configuration related to an NBL development test series. In addition, the PL ensures that all requested hardware and hardware configurations have been properly analyzed and approved for use. This includes, but is not limited to; Structural analysis, tip-over analysis, TRR's completed, Quality Safety and Acceptance Reviews (QSARs) completed, no outstanding Discrepancy Reports (DRs) that would impact the test, etc. For any new hardware developed for a test the PL assists the FL to ensure it meets requirements. The PL also Interfaces with other NBL teams to resolve equipment and configuration issues that arise before or during the test.

F. Flight Crew Office (CB)

The Crew Office supports NBL activities in a number of roles. For crew training they are the test subjects that are being trained to prepare for on orbit EVA. In this capacity they are required to prepare in advance by studying the hardware, procedures, and constraints associated with the tasks required of them. This is usually done in a class known as the 1G. This class is led by the Instructor and delivers the basic information needed for each tasks. It usually demonstrates the hardware of the task and the tools utilized. The crew then takes this information and prepares to execute the training.

For NBL development tests, the Crew Office supports in multiple roles. The Crew Office traditionally provides test subjects that have EVA experience and utilize that experience to evaluate whether or not the hardware is acceptable. In addition to the test subjects these tests usually have a Crew Office System Expert following the test to ensure that an integrated crew approach is taken. The Crew Office test team works together to deliver a concise crew opinion in either a formal or a verbal format. The formal format is traditionally documented in a report known as the Crew Consensus Report (CCR).

In addition to the testing roles, the Crew Office has representatives that meet with the NBL personnel on regular intervals to ensure that the overall operation is working smoothly. These personnel address crew issues with the NBL, NBL issues with crew, hardware issues, and any other concern that may interfere with nominal operations. These individuals make sure an open door policy exists between both organizations.

The ability to support the testing at the NBL requires that the Crew Office maintain a number of NBL SCUBA- and Suit-certified personnel. Their participation in NBL activities ensures that the test teams get the quality of data collection they are looking for while at the same time assist the crew with understanding the hardware.

Table 2 summarizes the how the responsibility for providing hardware (i.e., mockups, test articles, support equipment, and design and fabrication) and test support personnel is shared between NASA and the contractor organizations.

Table 2: Test Team Responsibilities

EDVT (Jacobs/EC7)	
Hardware	Support
<ul style="list-style-type: none">N/A	<ul style="list-style-type: none">Test conductorsTest integration and coordinationGuest diversDocumentation, including test plan, procedures, and final report
Boeing, Lockheed Martin, or Other Hardware providers	
Hardware	Support
<ul style="list-style-type: none">N/A	<ul style="list-style-type: none">Engineering test support
NBL Operations Contractor (DX12)	
Hardware (for example)	Support
<ul style="list-style-type: none">All Space Station elementsAll translation aids, including gap spanners installed on all modules in flight configuration	<ul style="list-style-type: none">NBL standard consoles and functionsNBL support personnel (utility and safety divers, test safety officer)

Hardware (for example)	Support
<ul style="list-style-type: none"> • Mobile Transporter/Mobile Base System (MT/MBS) • SSRMS • All ORUs • Cables, connectors, cable bags • Shields • Support stands • Underwater 35-mm photographic cameras • Underwater float video cameras • Underwater pan and tilt cameras 	<ul style="list-style-type: none"> • Underwater video and photographic support divers • Mockup integration

MOD (DX3)

Hardware	Support
<ul style="list-style-type: none"> • N/A 	<ul style="list-style-type: none"> • Test engineering and development support • Flight procedure development • Mockup requirements development

Crew Office (CB)

Hardware	Support
<ul style="list-style-type: none"> • N/A 	<ul style="list-style-type: none"> • Test engineering and development support • Crew test support coordination • Crew test subjects • Test documentation [Crew Consensus Report (CCR)]

EVA Office (XA)

Hardware	Support
<ul style="list-style-type: none"> • N/A 	<ul style="list-style-type: none"> • Test integration and development support

Suit Contract (USA)

Hardware	Support
<ul style="list-style-type: none"> • EMUs (up to three) and life support systems • High-fidelity and Neutrally Buoyant (NB) EVA tools 	<ul style="list-style-type: none"> • Suit engineer • Suit technicians • EVA tool delivery and logistics

VI. Conducting the Test

A. Daily Operations

On the morning of the test TCs and Suit Subjects meet at the tool setup area on the pool deck to run through the day's objectives, take a last look at some of the mockups, make final selection on tools for drop in the pool, and set up Mini Workstations (MWS). The TC also gives any final event instructions to the FL, PL, and divers who are present on the pool deck at this time and help resolve any last-minute issues.

In the morning dive brief the TC discusses event details such as subjects, order of objectives, special test conditions and hazards, etc. Once the brief is completed the TC agrees on a duty station call time (suit donning start time) with the Test Director (TD) and provides last-minute guidance to the subjects before they proceed to suit donning, dive and weighout. The TC starts conducting the test from console once weighout is complete and handover is received from the TD. The TC hands the test back over to the Test once the test objectives are completed or the end time designated by the TD is reached. Test days end with a post-dive de-brief during which

any hardware or safety issues are reviewed and the Test Team collects data and comments from the subjects regarding their performance of the objectives.

B. Working Console and Real-Time Decision-Making

The NBL provides a daily pool camera map showing numbered locations of cameras available for display on monitors in the TC booth. Based on this camera map the TC configures cameras to monitors for optimal viewing of the tasks as they are carried out. Once the TD hands over the test, the TC gives minute-by-minute, task-by-task direction to the subjects and divers using the Detailed Test Procedures (DTPs) and any real-time inputs from the rest of the test team.

Objectives are completed according to a pre-established priority order however special test day conditions such as mockup troubleshooting, pool-use conflicts, delayed starts, suit issues, or time shortages may force a TC to make midway decisions to drop, re-order or modify tasks. The TC must be constantly thinking ahead five minutes to several hours and conduct the test accordingly. As tasks are in work divers must be directed to prepare hardware and configure tools such as Articulating Portable Foot Restraints (APFRs) for succeeding tasks to ensure that delays and crew idle time in the water are minimal. The TC also directs divers to take any necessary photos of tasks being performed. Subjects generally complete objectives as a team but most often a TC will need to split them between objectives for better use of pool time. This creates an added layer of complexity to the test conducting task, since two separate sets of subject and diver commands must be managed simultaneously without confusion. Yet another layer of complexity is added when the station (and/or previously the shuttle) robotic arm is used in the test. The arm operator must be in constant communication with subjects and TD to perform triple-checks during any robotic motion, which changes the dynamics of the test and must be accounted for.

The goal is to complete all test objectives with each pair of subjects. Regardless of whether all objectives are completed, at 1500 hours (or test start time plus 6 hours, whichever is earlier) TC must hand control back to TD who ends the test and directs the suit doffing process.

C. Data Collection

The test team collects written data in many forms during the test. For each task the TCs and Crew Office rep make note of how successfully it is accomplished, any tool or foot restraint settings that worked, subject comments on the hardware, mockup issues or anomalies, and if applicable, adjustments to the DTPs. TC notes are later used to compile the EDVT Test Report. Crew Office rep notes are used to compile the Crew Consensus Report (CCR), which becomes a subset of the EDVT Test Report. Hardware reps take note of design comments from the subjects. Test subjects fulfill a key requirement in the process of data collection since their comments and critiques of the hardware and procedures are used to modify and improve the hardware and/or procedures for future tests in a given series. Rapid performance of test operations is not a goal of testing. In fact, crewmembers are briefed and encouraged to take their time and provide thoughtful comments.

Data is also collected by the NBL via three types of instrumentation:

- a. Audio recording: The test subject's electrical cable in the life support umbilical and the top-side personnel's headsets provide two-way communication, which is recorded on videotape throughout the test.
- b. Video recording: Four-channel, continuous Closed-Circuit Television (CCTV) coverage is derived from underwater stationary pan and tilt video cameras and two underwater hand-held (float) video cameras (only two channels are recorded simultaneously). The cameras are prepositioned for maximum data and large-scale coverage. The float camera operators are instructed to capture the small-scale activity.
- c. Still photography: A single diver with an underwater 35-mm camera is directed to record hardware and operations, as appropriate or directed by the TC. Many of these photos are later used in the EDVT Test Report and CCR.

VII. Reports

A. EDVT Reports

Within three days of test series completion, EDVT releases a Quick Look Report containing the list of objectives accomplished, any safety issues or anomalies recorded, and a few key photos from the test series. EDVT then generates a Test Report which encompasses any delta objectives, hardware changes, final test configuration, observations and results, Detailed Test Procedures, along with the entire CCR as part of the Appendix. This report is released within 8 weeks after the last NBL run (depends on receipt of CCR, any additional loads data or data that may require longer time to compile).

B. Crew Consensus Report (CCR)

The Astronaut office has the unique responsibility to execute operations in space. Spaceflight operations are very complex and dangerous. Spaceflight experience can be used to assist future hardware designers with areas where their designs may have issues or may not adequately meet the operational environment as envisioned. In order to address the transfer of this experience to designers the astronaut office uses The Crew Consensus Report. This report is the official position of the astronaut office on technical matters. These reports take multiple experienced crews and document their combined opinions on hardware and operational issues.

When combined with NBL testing the Crew Consensus Report is a very advantageous tool for any spaceflight hardware designer working on external hardware. The complexity of EVA makes it very difficult to perform even simple tasks such as turning bolts. Placement of stability aids, support hardware, or obstructions can easily make the task undoable. Performing evaluations in a simulated zero gravity environments with life size hardware provides the ability to actually perform the task as expected on orbit. Once a test is completed the crew office meets together and rates the test objectives, EVA hardware and tasks for acceptability or unacceptability based on the criteria in Table 3. Six crewmembers are required to form a crew consensus. The CCR is released within 4 weeks of test series completion.

Table 3: EVA Hardware and Task Ratings

Category	Description
Acceptable (A)	Design changes are not required, although recommendations may be included to improve hardware operations.
Unacceptable 1 (U1)	Design changes are required. Retesting is not required; however, drawing review and/or shirtsleeve inspection of flight or high-fidelity hardware is required to verify adequacy of design changes.
Unacceptable 2 (U2)	Design changes are required. Retesting is required to verify the adequacy of design changes.
Inconclusive (I)	No crew consensus can be reached due to inadequate hardware fidelity, inappropriate test conditions or environment, or insufficient number of test subjects used. Retesting will be required unless specified otherwise.

In addition recommendations of how the hardware should be built, what tools can interface properly, and what extra hardware may be required are also provided in the CCR to assist designers with making the evaluated hardware EVA-compatible.

The Crew Consensus Report is the formal documentation that is used by program personnel to trace requirements verifications. For operational type requirements that need crew intervention to be successful, the Crew Consensus Report is the official document that verifies the requirement can be considered acceptable and no further modifications of hardware are required unless stated in the report. Those hardware designs or operations rated “unacceptable” or “inconclusive” require disposition and closure through the EVA Analysis and Integration Team (AIT) at NASA JSC.

VIII. Other NBL Uses and Future Look

In addition to EVA type hardware evaluations, the NBL can provide internal micro gravity evaluations of hardware as well. It has the ability to allow test subjects the SCUBA dive in a internal cabin environment and evaluate reach to controls and instruments and/or assemble experiments or other hardware needed in micro gravity environments. These can also be done on a task basis utilizing the ability to build mockups of hardware and practice tasks of assembly, maintenance, and operation in a virtually similar environment to spaceflight.

As NASA looks forward to operating in space with the International Space Station, Commercial initiatives, and exploration activities, the NBL becomes a very important part of the development of all of these. The use of the NBL for the ISS has already been documented and for all future activities external to the ISS, the NBL will be required to provide the high level of confidence to ensure a successful operation. For external experiments, external

maintenance, and for exploration hardware that need to be in the space environment, the NBL is the place to make to test out whether the hardware is EVA compatible or not.

For Commercial initiatives that will be required to operate in conjunction with the ISS, the NBL will provide the needed external hardware interface answers to assist commercial designers with evaluating their hardware for EVA compatibility. From a requirements standpoint this may be few, but from a history of spaceflight, it will be required more than first envisioned.

In order to provide services to commercial customers, the NBL and test team know that they will need to be especially adaptable to unique operational needs, new paradigms, highly prototypical hardware, completely differing perspectives, shorter more intense timelines, and vastly differing methodologies from what NASA has been accustomed to in recent decades. There will be a need to make accommodations that require complete shifts in operational support day to day, week to week. Future customers may have much more organic, bare-bones approaches to spaceflight hardware development. NASA is already becoming more flexible, open-minded, creative, and resourceful than ever before in supporting these new customers.

For Exploration activities, the NBL will provide the place to evaluate the operational concepts needed to perform EVA on asteroids, lunar, and Mars type environments. The development of these concepts, the hardware needed to execute these concepts, and the philosophy of what will be done during the exploration of space will get its beginnings in the NBL.

IX. Conclusion

The NBL is an excellent facility to assist with determining human interface in a zero gravity environment. It has traditionally been used to evaluate EVA hardware during its conceptual and design phase. It has been used extensively to evaluate extremely accurate mockups of spaceflight hardware to determine how the user interface is affected by the design. It has been essential for crew training on highly intricate EVA activities.

The experience of these evaluations and the test teams as formed to execute these evaluations provide a service that over the period of a life cycle save a large percent of budget but ensuring the hardware meets its operational requirement. Future commercial spaceflight adventures can benefit from the experience as performed at the NBL. As the boundaries of space increase, preparing humans to operate in micro gravity will become more important and the NBL is the facility that much of this preparation can be done.

Because of the visibility that the NBL enjoys in the eyes of the American public and Congress, it is imperative that it maintain its place as a showpiece of NASA's vision, competence, and as a window on current and future human spaceflight aspirations.

Appendix

Acknowledgments

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